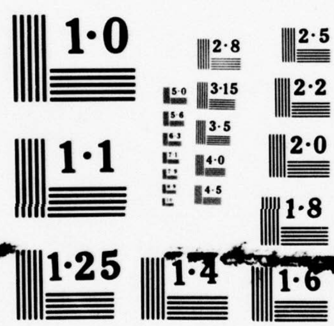
AD-A055 497 LEHIGH UNIV BETHLEHEM PA INST OF FRACTURE AND SOLID --ETC F/G 11/6
ON UNDERSTANDING ENVIRONMENT ENHANCED FATIGUE CRACK GROWTH. A P--ETC(U)
MAY 78 R P WEI N00014-75-C-0543
UNCLASSIFIED IFSM-78-90 NL

| OF |
ADA
055497

END
DATE
FILMED
8 -78
DDC


1·0
2·8
2·5
5·0
3·15
2·2
5·6
3·5
2·0
1·1
4·0
4·5
1·8
1·25
1·4
1·6

12

B.S.

IFSM-78-90

INSTITUTE OF FRACTURE AND SOLID MECHANICS

LEHIGH UNIVERSITY

HOMO MINISTER ET INTERPRES NATURAE · LEHIGH UNIVERSITY · FOUNDED BY ASA PACKER 1865

ON UNDERSTANDING ENVIRONMENT ENHANCED FATIGUE CRACK GROWTH A PERSPECTIVE VIEW (1968-1977)

by

R. P. Wei

May 1978

Technical Report No. 7

Office of Naval Research

Contract N00014-75-C-0543, NR 036-097

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER 14 IFSM-78-90, TR-7	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 6 On Understanding Environment Enhanced Fatigue Crack Growth. A Perspective View (1968-1977).		5. TYPE OF REPORT & PERIOD COVERED 9 Technical Report, No. 7
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) 10 Dr. R. P. Wei		8. CONTRACT OR GRANT NUMBER(s) Contract N00014-75-C-0543 15
9. PERFORMING ORGANIZATION NAME AND ADDRESS Lehigh University Bethlehem, PA 18015		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NR 036-097
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Department of the Navy Arlington, Virginia		12. REPORT DATE 11 May [redacted]78
		13. NUMBER OF PAGES 27 12 30p.
14. MONITORING AGENCY NAME & ADDRESS (*if different from Controlling Office*)		15. SECURITY CLASS. (*of this report*) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (*of this Report*)

This document has been approved for public release and sale; its distribution is unlimited.

17. DISTRIBUTION STATEMENT (*of the abstract entered in Block 20, if different from Report*)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*)

Fatigue Crack Growth; Corrosion Fatigue; Fracture Mechanics; Surface Chemistry, Metals

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

Corrosion fatigue (CF) is a generic term that is used to describe the phenomenon of cracking (including environment enhanced fatigue crack growth) in materials under the conjoint actions of an applied cyclic stress and a corrosive (aggressive) environment. It has been recognized as an important cause for failure of engineering structures. Characterization and understanding of corrosion fatigue are essential to service life prediction, fracture control, and the development of fatigue resistant alloys. Quantitative characterization

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*)

407 099

JOB

and understanding have been hampered by the complexity of the problem, difficulties in separating the effects associated with crack initiation and with crack growth, and the absence of truly interdisciplinary attack of this problem.

With the development of fracture mechanics technology since the mid 1950's and the increased emphasis on fatigue crack growth, quantification of environment enhanced fatigue crack growth has now been placed on a reasonably firm basis in terms of both steady-state and transient responses. Understanding of the chemical processes that control environment enhanced fatigue crack growth are beginning to emerge from coordinated mechanical, metallurgical and chemical studies. A perspective view of the progress during the past decade is given. Areas and directions for future research are discussed.

ON UNDERSTANDING ENVIRONMENT ENHANCED FATIGUE CRACK GROWTH
A PERSPECTIVE VIEW (1968-1977)

by

R. P. Wei
LEHIGH UNIVERSITY
Bethlehem, PA 18015, USA

ABSTRACT

Corrosion fatigue (CF) is a generic term that is used to describe the phenomenon of cracking (including environment enhanced fatigue crack growth) in materials under the conjoint actions of an applied cyclic stress and a corrosive (aggressive) environment. It has been recognized as an important cause for failure of engineering structures. Characterization and understanding of corrosion fatigue are essential to service life prediction, fracture control, and the development of fatigue resistant alloys. Quantitative characterization and understanding have been hampered by the complexity of the problem, difficulties in separating the effects associated with crack initiation and with crack growth, and the absence of truly interdisciplinary attack of this problem.

With the development of fracture mechanics technology since the mid 1950's and the increased emphasis on fatigue crack growth, quantification of environment enhanced fatigue crack growth has now been placed on a reasonably firm basis in terms of both steady-state and transient responses. Understanding of the chemical processes that control environment enhanced fatigue crack growth are beginning to emerge from coordinated mechanical, metallurgical and chemical studies. A perspective view of the progress during the past decade is given. Areas and directions for future research are discussed.

Key Words: Fatigue Crack Growth, Corrosion Fatigue, Fracture Mechanics, Surface Chemistry, Metals

Invited Paper: For ASTM Symposium on Fatigue Mechanisms to be held in Kansas City, MO, May 22-23, 1978.

INTRODUCTION

Metal fatigue as an engineering problem has been well recognized. It is one of the major causes, if not the major cause, for failure of engineering structures in service. Considerable engineering and scientific efforts have been devoted, especially during the past two decades, to the characterization of fatigue response and to the understanding of the mechanisms for fatigue. Such characterization and understanding are essential to service life prediction, fracture control, and the development of fatigue resistant alloys. Quantitative characterization and understanding, however, have been hampered by the complexity of the problem, by difficulties in separating the effects associated with crack initiation from those associated with crack growth, and by the influences of external chemical environments on both the initiation and growth processes.

With the development of fracture mechanics technology since the mid 1950's and the increased concern with fatigue crack growth in many applications, it was more or less natural to consider the processes associated with fatigue crack growth separately. This separation narrowed the problem scope considerably and has been by and large beneficial. By restricting attention to the growth of a dominant crack[1/], one essentially circumvents nearly all of the issues associated with crack initiation. Characterization of crack growth response can be and has been carried out in a straight

1/ Delineation between initiation and growth is not well defined or defineable. A dominant crack here implies that the planar dimensions of the crack are large with respect to the microstructural (e.g., grain) sizes.

forward manner, and the data utilized directly for estimating service performance. In terms of understanding fatigue crack growth, the problem can be further divided into two areas as follows:

- o Mechanisms for fatigue crack growth
- o Environment enhancement of fatigue crack growth

The first of these two areas is concerned with understanding the purely mechanical processes for fatigue; that is, fatigue in the absence of environmental influences. The second area deals with understanding fatigue crack growth response under the conjoint actions of mechanical fatigue and chemical attack. Progress has been made in both of these areas during the past twenty years and has been documented in a number of review articles and in the proceedings of several symposia [1-6]. In this paper, a perspective view of the progress during the past ten years in the second of these two areas, that is, towards understanding environment enhanced fatigue crack growth, is given. The need for an interdisciplinary approach to the problem and the development of such an approach are described. The usefulness of this approach is discussed in terms of recent experimental results. Areas and directions for future research are considered.

THE FRACTURE MECHANICS BASIS FOR FATIGUE CRACK GROWTH STUDIES

One of the principal obstacles in the development of understanding of the various aspects of fatigue had been the difficulty in relating material response to the appropriate driving forces in

a consistent and quantitative manner. By isolating the problems of fatigue crack growth for study, some simplification has been made possible. The material response then becomes simply the rate of fatigue crack growth and can be readily measured. The appropriate driving force has been defined through the development of linear fracture mechanics, and the application of this technology to fatigue crack growth problems [7-10]. Because crack growth is most likely to proceed from the highly stressed region at the crack tip, it is most appropriate to characterize the mechanical crack driving force in terms of the crack tip stress-intensity factor, K, or stress intensity factor range, ΔK [7-10]. The assumptions, utility, and restrictions of this approach have been discussed in detail elsewhere [7-10]. Two of the following three related loading variables are commonly used for characterizing fatigue crack growth: maximum stress intensity factor, K_{max}; cyclic stress-intensity factor range, ΔK, ($\Delta K = K_{max} - K_{min}$); and stress ratio, or load ratio, R, ($R = K_{min}/K_{max}$).2/ (K_{min} is the minimum stress-intensity factor in a load cycle.) These variables have their counterparts in conventional fatigue analysis. They are the maximum stress, σ_{max}, stress range, $\Delta\sigma$, and stress ratio, R, ($R = \sigma_{min}/\sigma_{max}$), respectively.

SOME SIGNIFICANT VARIABLES AFFECTING FATIGUE

Many variables can influence fatigue crack growth. Some of

2/ These three parameters are interrelated. Only two of the three need to be specified. For loading into compression, stress intensity factor is not defined and the effective K_{min} is either zero or nearly zero. An operational definition of $\Delta K = K_{max}$, with stress or load ratio (R) specified in terms of the applied stress or load is being adopted for $R \leq 0$ [12]. The reader should examine published fatigue crack growth data to determine how ΔK was defined.

the significant variables are listed in the following, along with the aforementioned loading variables [11]:

Mechanical Variables

- Maximum stress or stress-intensity factor, σ_{max} or K_{max} [2/]
- Cyclic stress or stress intensity factor range, $\Delta\sigma$ or ΔK [2/]
- Stress ratio, or load ratio, R, [2/] i.e., ratio of minimum to maximum stress (load) or stress-intensity factor in one cycle
- Cyclic load frequency, f
- Cyclic load waveform (for constant-amplitude loading)
- Load interactions in variable amplitude loading
- State of stress
- Residual stress.

Geometrical Variables

- Crack size and relation to component dimensions
- Crack geometry
- Component geometry adjoining crack
- Stress concentrations associated with design.

Metallurgical Variables

- Alloy composition
- Distribution of alloying elements and impurities
- Microstructure and crystal structure
- Heat treatment
- Mechanical working
- Preferred orientation of grains and grain boundaries -- (texture)

- o Mechanical properties (strength, fracture toughness, etc.).

Environmental Variables

- o Temperature, T
- o Types of environments -- gaseous, liquid, liquid metal, etc.
- o Partial pressure of damaging species in gaseous environments, p_i
- o Concentration of damaging species in aqueous or other liquid environments, C_i
- o Electrical potential, ϕ
- o pH
- o Viscosity of environment, η
- o Coatings, inhibitors, etc.

Many of these variables have been examined, and the results are summarized in a number of review articles [5,10,13-16].

PHENOMENOLOGICAL OBSERVATIONS

Serious studies of the influence of environment on fatigue crack growth (vis-a-vis, fatigue per se) began in the middle of 1960 and continued through the past decade [5,10,13,14]. Work during this period was concerned mainly with characterizing fatigue crack growth response, and with examining the influences of the different variables on environment enhanced fatigue crack growth. Development of mechanistic understanding was by-and-large by inference and was often incidental to the studies. The results from the various investigations have been reviewed in detail previously [5,10,13,14] and will not be repeated here.

It is important to note that crack growth is influenced by a broad range of loading variables, some of which can interact with the environment. Many of the observed effects of loading variables can be traced directly to environmental interactions [5,10,13,14]. On the basis of data gathered over the past 15 years, the steady-state response of fatigue crack growth to environments may be grouped into three basic types and be discussed in relation to K_{Iscc} [3/], Figure 1 [10]. Type A behavior is typified by the aluminum-water system. Environmental effects result from the interaction of fatigue and environmental attack [5,10]. Type B behavior is represented by the hydrogen-steel system [18]. Environmental crack growth is directly relatable to sustained load crack growth, with no interaction effects [5,10,18]. Type C represents the behavior of most alloy-environment systems. Above K_{Iscc}, the behavior approaches that of Type B, whereas, below K_{Iscc}, the behavior tends toward Type A, with the associated interaction effects. The transition between the two types of behavior is not always sharply defined.

Extensive work on the aluminum alloys (Type A behavior) indicates that practically all aluminum alloys are susceptible to environment-enhanced fatigue crack growth [5,19,20]. The environmental effect is a function of thickness or state of stress. There is no effect of frequency for crack growth in an inert

3/ K_{Iscc} is the apparent threshold K level for stress-corrosion cracking and is defined as the asymptotic value of K as the rate of crack growth under sustained load approaches zero [17]. Environment enhanced crack growth can and does occur below K_{Iscc} in fatigue, and K_{Iscc} serves only as a convenient line of demarcation.

environment and a small effect in fully saturated and aqueous environments. The effect of frequency can be very large in partially saturated environments and is related to the partial pressure of water vapor [5,21,22]. The influence of temperature can be quite strong and depends on the mechanical crack driving force, ΔK [5,23].

Work on Type B systems [5,14,24-26] indicates that fatigue crack growth in an aggressive environment depends on frequency, stress or stress-intensity level, stress ratio and waveform. The influences of all of these loading variables may be accounted for, to a fair degree of approximation, by the simple superposition model proposed by Wei and Landes [18] which relates fatigue and sustained load crack growth.

In studies by Barsom [27] and Gallagher [28], it was found that environment-enhanced fatigue crack growth below K_{Iscc} in certain steels (exhibiting Types A or C response) is a function of both frequency and waveform. Environmental effect was found to be nearly zero at high frequencies, reached a maximum at an intermediate frequency, and then showed a slight apparent decrease, or no decrease, with further reduction in frequency [27,28]. Environmental effect was observed only for certain waveforms (such as sine and triangle) and not for others (such as square waves) [27]. These waveform effects were not observed on an aluminum alloy tested in distilled water [29] and on a high-strength steel tested in water vapor [30,31].

In addition to the steady-state response, a number of non-steady-state crack growth behaviors have been reported. Nonsteady-

state behavior refers to cases in which the rate of crack growth differs from the steady-state rate for the prevailing K or ΔK, and is transitory in nature [17]. Nonsteady-state fatigue crack growth has been observed at the start of fatigue loading and following "prolonged" load interruption [24], and with changes in cyclic-load frequency [31] in high-strength steels. These nonsteady-state phenomena have been shown to be associated principally with fatigue crack growth in aggressive (corrosive) environments [24,30,31].

Although one had hoped to infer mechanistic understanding from these various studies, it became quite obvious by 1970 that the key issues were not being addressed, and that the parallel, though separate, studies by researchers in chemistry, materials science and mechanics were not adequate. A search for an integrated interdisciplinary approach was begun in earnest.

AN INTERDISCIPLINARY APPROACH TO FATIGUE STUDIES

The search for an integrated interdisciplinary approach parallel similar development in the area of sustained-load crack growth (or stress corrosion cracking), and is based on the following premises gleaned from the available experimental data:

- Environmental influences are superimposed on the basic process of fatigue and can be studied without the need for understanding the underlying mechanism for fatigue crack growth. (Note that the converse is not true in that verification of proposed mechanisms for fatigue cannot be made without properly accounting for environmental

effects).

- o The controlling processes (e.g., surface reaction, diffusion, etc.) for crack growth under sustained load and in fatigue are expected to be essentially the same for a given material-environment combination.
- o The observed influences of loading variables, in the absence of creep, are principally environmental effects. These effects relate to both steady-state and nonsteady-state responses.
- o Quantitative understanding of environment enhanced fatigue crack growth requires a "link" between the kinetics of crack growth and the kinetics of the relevant controlling processes.
- o Quantitative understanding, in all likelihood, would require all relevant (chemical, mechanical and metallurgical) experiments to be carried out on the same material under essentially identical environmental conditions to permit direct comparison.

The need to involve corrosion and surface chemists, material scientists and fracture mechanicians becomes immediately obvious. By the same token, the key issues concerning the nature and kinetics of the controlling processes, and their influences on steady-state and nonsteady-state crack growth can be readily identified. The difficulty now lies in establishing a "link" between the kinetics of crack growth and those of the relevant controlling process. This crucial link, however, became available through investigations

on the kinetics of sustained-load crack growth [17]. These investigations showed that there is a stage of crack growth in which the rate is essentially independent of the mechanical driving force. This independence indicates that the rate of sustained-load crack growth is limited by the underlying controlling process, and provides an avenue for identifying the rate controlling process by direct comparisons between the rates and activation energies for crack growth and for the various probable controlling processes.

As an illustration of this integrated interdisciplinary approach, results from recent studies of sustained-load and fatigue crack growth in an AISI 4340 steel in water/water vapor are described briefly [31,32].

AN ILLUSTRATION OF THE INTERDISCIPLINARY APPROACH

One of the key issues for crack growth in high-strength steels exposed to water/water vapor relates to the identity of the rate controlling process for crack growth [32], see Figure 2. To address this issue, sustained-load crack growth experiments were carried out on an AISI 4340 steel in hydrogen and in water, to determine the kinetics of crack growth as a function of temperature. Companion experiments were carried out on the same steel to determine the kinetics of water-metal surface reaction using Auger electron spectroscopy (AES). These studies were supplemented by detailed fundamental studies of reactions of water vapor with iron single crystal of known orientation by AES and LEED (low energy electron diffraction) [33], and by AES analysis of the elemental

composition of fracture surfaces produced by environment assisted crack growth [34]. Through these coordinated interdisciplinary studies and comparisons of activation energies for crack growth and for surface reaction (see Figure 3), the rate limiting process for crack growth was identified as a slow step in the reaction of water/water vapor with iron and/or iron carbide (vis-a-vis, hydrogen diffusion) [32-34]. This reaction step is associated with the nucleation and growth of oxide on the surface, and the presumed concommitant production of hydrogen [32].

Having identified the rate limiting process for crack growth, its implication in terms of fatigue crack growth response was examined [31]. The effect of cyclic-load frequency on fatigue crack growth in water vapor at 585 Pa (4.4 torr) at room temperature is illustrated in Figure 4, and the influence of changing frequency on crack growth response under constant load-amplitude fatigue is illustrated in Figure 5. These results confirm the existence of a significant effect of frequency at K_{max} levels well below that required for producing significant crack growth under sustained loads (i.e., below K_{Iscc}) [27,28]. The extent of crack growth, following a change in frequency, that is required to re-establish steady-state appeared to depend on the magnitude of the frequency change (for example, from 1 to 0.1 Hz versus 10 to 0.1 Hz) and on crack length or ΔK. Since frequency effect was absent in an inert environment [5,30], the observed transient phenomenon was attributed to interactions with the environment [31]. Fractographic examinations of fracture surfaces produced at the different loading frequencies showed that at high frequency (viz., 10 Hz)

the morphology was akin to that for "pure" (mechanical) fatigue. At the lower frequencies (i.e., below 1 Hz), the morphology exhibited increasing amounts of intergranular separation along prior-austenite grain boundaries that is typical for sustained-load crack growth in water/water vapor [31,32].

These observations, taken _in toto_ and in conjunction with the earlier study on sustained-load crack growth [32], provided a rational basis for explaining environment enhanced fatigue crack growth response in this case. Fatigue crack growth rate in an aggressive environment, $(da/dN)_e$, is considered to be the sum of two components -- one for "pure" fatigue, $(da/dN)_r$, and one for the environmental contribution, $(da/dN)_{cf}$.

$$(da/dN)_e = (da/dN)_r + (da/dN)_{cf}$$

More generally,

$$\begin{aligned}(da/dN)_e &= (da/dN)_r + (da/dN)_{cf} + (da/dN)_{scc} \\ &= (da/dN)_r + (da/dN)_{cf} + \int_0^t [da/dt(K)]dt\end{aligned}$$

where $(da/dN)_{scc}$ is the contribution by sustained-load crack growth at K levels above K_{Iscc} [18]. Environmental contribution is expected to involve a region of "embrittled" or "damaged" material ahead of the crack tip (i.e., "volume embrittlement" vis-a-vis "surface embrittlement")[4/]. Because the rate controlling process is that of surface reaction, the size of this region would depend on the time available for reaction (viz., cyclic load period) and

4/ Hydrogen embrittlement is considered to be the responsible mechanism, although the details of this mechanism is not understood [31,32].

on the reaction kinetics.

A conceptual model was suggested, in which a steady-state zone of "embrittled" material existed ahead of the crack tip under steady-state conditions (i.e., for prescribed ΔK, cyclic load frequency and environment), and is illustrated schematically in Figure 6 [31]. The damaged or embrittled zone is depicted as circles, representing some appropriate hydrogen concentration contours ahead of the crack tip. Because more hydrogen is produced at the lower frequencies (longer exposure time), the size of the damaged zone and/or the hydrogen concentration within the zone are expected to be larger at these frequencies (Figure 6). On each cycle of loading, the crack would extend, in one step, through a fraction of this zone. Following this increment of growth, a steady-state zone is re-established ahead of the new crack tip through reactions of the environment with the freshly created crack surface, and hydrogen diffusion and redistribution. The existence of environmental effects at K_{max} levels below K_{Iscc} in fatigue is not inconsistent with the definition of K_{Iscc} (defined for sustained loading), since fatigue is a more proficient process for producing fresh surfaces to react with the environment to produce the subsequent embrittlement.

The model appeared to be consistent with the experimental data on crack growth kinetics and with the kinetics of surface reactions (see Figure 7) [31,32]. For the range of frequencies used in the fatigue experiments, at a water vapor pressure of 585 Pa, the surface reaction data suggested that the environmental

contribution[5/] should vary almost linearly with the cyclic load period or inversely with frequency (see Figure 7a). At high frequencies, environmental effect should be essentially negligible; at low frequencies, it should reach a maximum (or a saturation value). The general trend suggested by the model is consistent with data reported by Gallagher [28] for fatigue crack growth in HY-80 steel in 3.5 pct NaCl solution, by Vosikovsky [35] on a X-65 pipeline steel in sour (H_2S containing) crude oil, and by Bradshaw and Wheeler [21] on an aluminum alloy in water vapor. In the latter two material-environment combinations, the surface reaction rates are expected to be 6 to 8 orders of magnitude faster than that of the water-iron reactions [31-34]. The model also provided a reasonable explanation for the observed nonsteady-state response associated with changes in cyclic load frequency (see Figure 5) [31]. The nonsteady-state response was attributed to the process for establishing a new steady-state zone size following a change in loading frequency.

SUMMARY

The decade (1968-1977) is a period of considerable activity in the area of environment enhanced fatigue crack growth. Work during this period has contributed significantly to the phenomenological understanding of environment-enhanced fatigue crack growth (or corrosion fatigue), and has brought greater recognition

5/ The environmental contribution is represented by the difference of two empirical constants, $C-C_o$, determined by least-squares fit to the data in Figure 4 using $da/dN = C\Delta K^2$ [3]. This empirical relationship provided a useful basis for representing these data, but does not have general validity.

of the importance of this problem. As a result, corrosion fatigue is being explicitly considered in a diverse range of applications; for example, in aircraft structures, off-shore structures, highway bridges, transmission linepipes, and coal conversion systems. It has also brought a recognition that quantitative understanding of this important phenomenon would require well-coordinated interdisciplinary approaches that can address the relevant chemical, mechanical and metallurgical issues in concert. One such approach, incorporating fracture mechanics technology and modern surface analysis and metallurgical techniques, has shown considerable promise in developing understanding of environment enhanced crack growth in gaseous environments [31,32]. Considerably more studies are needed to develop understanding in other material-environment systems, particularly for aqueous environments. Similar approaches need to be developed for understanding the processes of environment assisted fatigue crack initiation.

The significant influence that environments (even those normally thought to be innocuous, such as moist air) can have on fatigue crack growth needs to be taken more seriously than before by those working on the mechanisms for fatigue crack growth. Since almost all of the proposed mechanisms do not explicitly include the influences of environment, one must be careful in selecting available data for use in model verification. By the same token, one should be extremely wary of generalizations concerning fatigue crack growth mechanisms that are formulated on

the indiscriminate use of existing data.

ACKNOWLEDGEMENT

Support of this work by the Office of Naval Research under Contract N00014-75-C-0543, NR 036-097, is gratefully acknowledged.

REFERENCES

1. Mechanisms of Fatigue in Crystalline Solids, (Proceedings of International Conference, Orlando, Florida, November 15-17, 1962), Acta Metallurgica, Vol. 11, 1963, pp. 639-828.

2. Fatigue -- An Interdisciplinary Approach, Syracuse University Press, 1964.

3. Fatigue Crack Propagation, ASTM STP 415, Am. Soc. Testing Matls., 1967.

4. CORROSION FATIGUE: Chemistry, Mechanics and Microstructure, NACE-2, Natl. Assoc. Corr. Engrs., 1972.

5. Wei, R. P., Journal of Engineering Fracture Mechanics, Vol. 1, 1970, pp. 633-651.

6. Hoeppner, D. W. and Krupp, W. E., "Prediction of Component Life by Application of Fatigue Crack Growth Knowledge", Report LR-25123, Lockheed-California Company, Burbank, California, 1972.

7. Paris, P. C., Fatigue -- An Interdisciplinary Approach, Syracuse University Press, 1964, pp. 107-132.

8. Johnson, H. H., and Paris, P. C., Journal of Engineering Fracture Mechanics, Vol. 1, No. 3, 1968, p. 3.

9. Wei, R. P., Proceedings of Conference -- Fundamental Aspects of Stress Corrosion Cracking, NACE-1, Natl. Assoc. Corr. Engrs., 1969, pp. 104-112.

10. McEvily, A. J., and Wei, R. P., CORROSION FATIGUE: Chemistry, Mechanics and Microstructure, NACE-2, Natl. Assoc. Corr. Engrs., 1972, pp. 381-395.

11. Wei, R. P., and Speidel, M. O., in CORROSION FATIGUE: Chemistry, Mechanics and Microstructure, NACE-2, Natl. Assoc. Corr. Engrs., 1972, pp. 379-380.

12. "Tentative Method of Test for Constant-Load-Amplitude Fatigue Crack Growth Rates Above 10^{-8} m/cycle", ASTM, 1977; (in the final stage of approval process).

13. Achter, M. R., ASTM STP 415, Am. Soc. Testing Matls., 1967, pp. 181-204.

14. Gallagher, J. P., and Wei, R. P., in CORROSION FATIGUE: Chemistry, Mechanics and Microstructure, NACE-2, Natl. Assoc. Corr. Engrs., 1972, pp. 409-423.

15. Hudson, C. M., and Raju, K. N., NASA TN D-5702, National Aeronautics and Space Administration, 1970.

16. Schijve, J., "Fatigue Crack Propagation in Light Alloy Sheet Material and Structures", Rept. MP 195, National Luchtvaartlaboratorium (Amsterdam), Aug. 1960.

17. Wei, R. P., Novak, S. R., and Williams, D. P., in AGARD Conference Proceedings No. 98, Specialists Meeting on Stress Corrosion Testing Methods (1971), and Materials Research and Standards, ASTM, Vol. 12, 1972, p. 25.

18. Wei, R. P., and Landes, J. D., Materials Research and Standard, ASTM, Vol. 9, No. 7, July 1969, p. 9.

19. Feeney, J. A., McMillan, J. C., and Wei, R. P., Metallurgical Transactions, Vol. 1, 1970, p. 1741.

20. Hartman, A., and Schijve, J., NLR Tech. Note MP 68001 U (1968).

21. Bradshaw, F. J., and Wheeler, C., Applied Materials Research, Vol. 5, 1966, p. 112.

22. Hartman, A., International Journal of Fracture Mechanics, Vol. 1, 1965, p. 167.

23. Wei, R. P., International Journal of Fracture Mechanics, Vol. 4, 1968, p. 159.

24. Miller, G. A. Hudak, S. J., and Wei, R. P., Journal of Testing and Evaluation, ASTM, Vol. 1, 1973, p. 524.

25. Bucci, R., "Environment Enhanced Fatigue and Stress Corrosion Cracking of a Titanium Alloy Plus a Simple Model for Assessment of Environmental Influence of Fatigue Behavior", Ph.D. dissertation, Lehigh University, 1970.

26. Landes, J. D., and Wei, R. P., Journal of Engineering Materials and Technology, Trans. ASME, Ser. H, Vol. 95, 1973, p. 2.

27. Barsom, J. M., in CORROSION FATIGUE: Chemistry, Mechanics and Microstructure, NACE-2, Natl. Assoc. Corr. Engrs., 1972, pp. 424-436.

28. Gallagher, J. P., "Corrosion Fatigue Crack Growth Behavior Above and Below K_{Iscc}", NRL Report 7064, Naval Research Laboratory, Washington, D. C., May 1970.

29. Hudak, S. J., Jr., and Wei, R. P., in CORROSION FATIGUE: Chemistry, Mechanics and Microstructure, NACE-2, Natl. Assoc. Corr. Engrs., 1972, p. 433.

30. Hutin, J. P., "Sub-Critical Crack Growth in AISI 4340 Steel in Water and Water Vapor", M.S. Thesis, Lehigh University, 1975.

31. Pao, P. S., Wei, W., and Wei, R. P., "Effect of Frequency on Fatigue Crack Growth Response of AISI 4340 Steel in Water Vapor", Proceedings of Symposium on Environment Sensitive Fracture of Engineering Materials (Held in Chicago, October 24-26, 1977), AIME (to be published).

32. Simmons, G. W., Pao, P. S., and Wei, R. P., "Fracture Mechanics and Surface Chemistry Studies of Subcritical Crack Growth in AISI 4340 Steel", Metallurgical Transactions A (submitted for publication in 1977).

33. Dwyer, D. J., Simmons, G. W., and Wei, R. P., Surface Science, Vol. 64, 1977, p. 617.

34. Wei, R. P., and Simmons, G. W., Scripta Metallurgica, Vol. 10, 1976, p. 153.

35. Vosikovsky, O., Corrosion, Vol. 32, 1976, p. 472.

FIGURE CAPTIONS

Figure 1: Types of fatigue crack growth behavior [10].

Figure 2: Schematic illustrations of various sequential processes involved in embrittlement by external gaseous environments. (Embrittlement reaction is depicted schematically by the Fe-H-Fe bond).

Figure 3: Correlation between (a) the kinetics of Stage II (rate limited) crack growth under sustained load and (b) the rate of water vapor/metal (carbide) surface reaction for an AISI steel [32].

Figure 4: Room temperature fatigue crack growth kinetics on AISI 4340 steel tested in dehumidified argon and in water vapor (below K_{Iscc}) at $R = 0.1$ [31].

Figure 5: Room temperature fatigue crack growth response resulting from changes in cyclic load frequency [31].

Figure 6: Schematic illustration of conceptual model for environment enhanced fatigue crack growth below K_{Iscc} [31].

Figure 7: Comparison between (a) the environment dependent component of fatigue crack growth as a function of cyclic load period and (b) the extent and normalized rate of reaction with water vapor as a function of exposure for an AISI 4340 steel at room temperature [31,32].

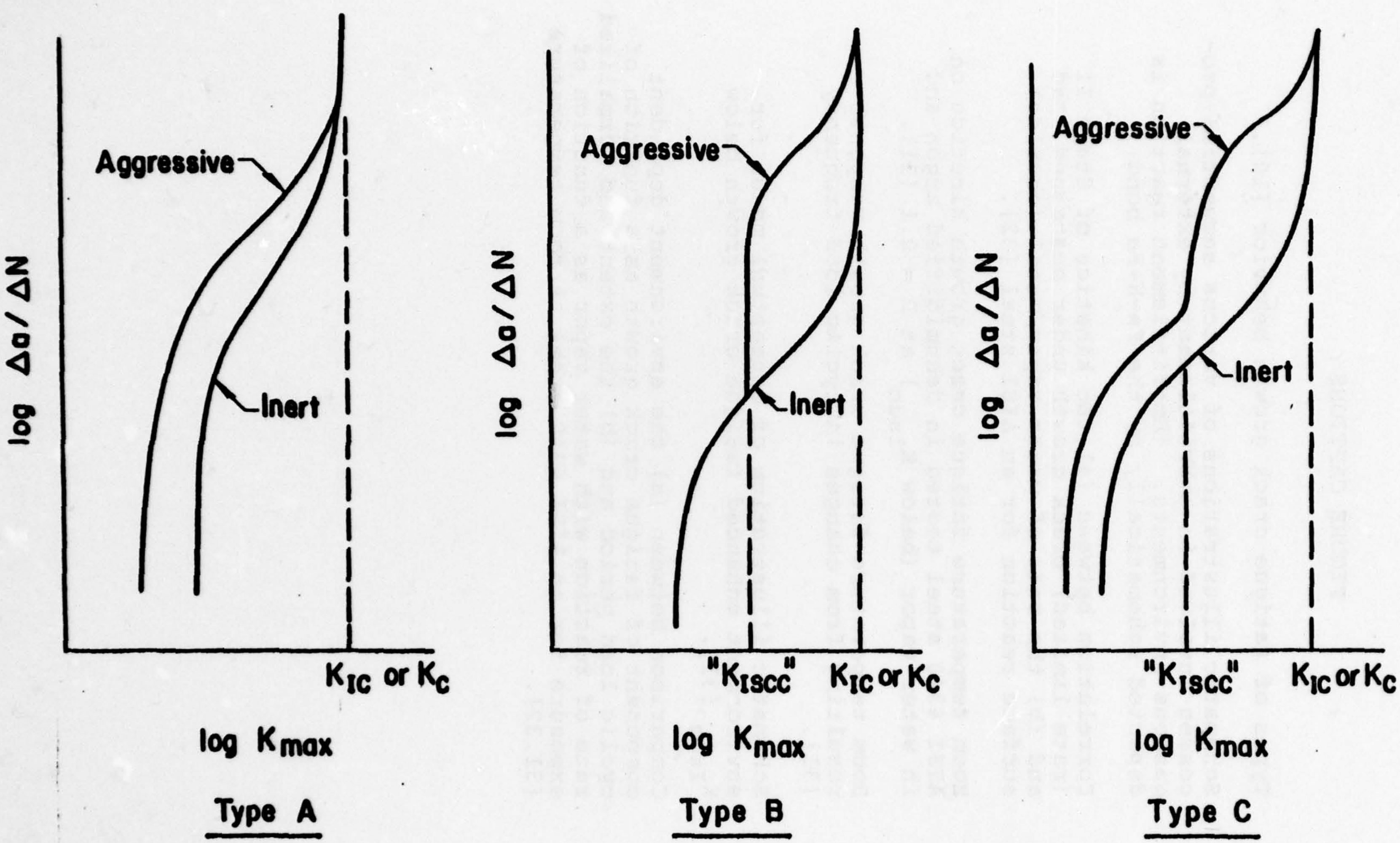


Figure 1: Types of fatigue crack growth behavior [10].

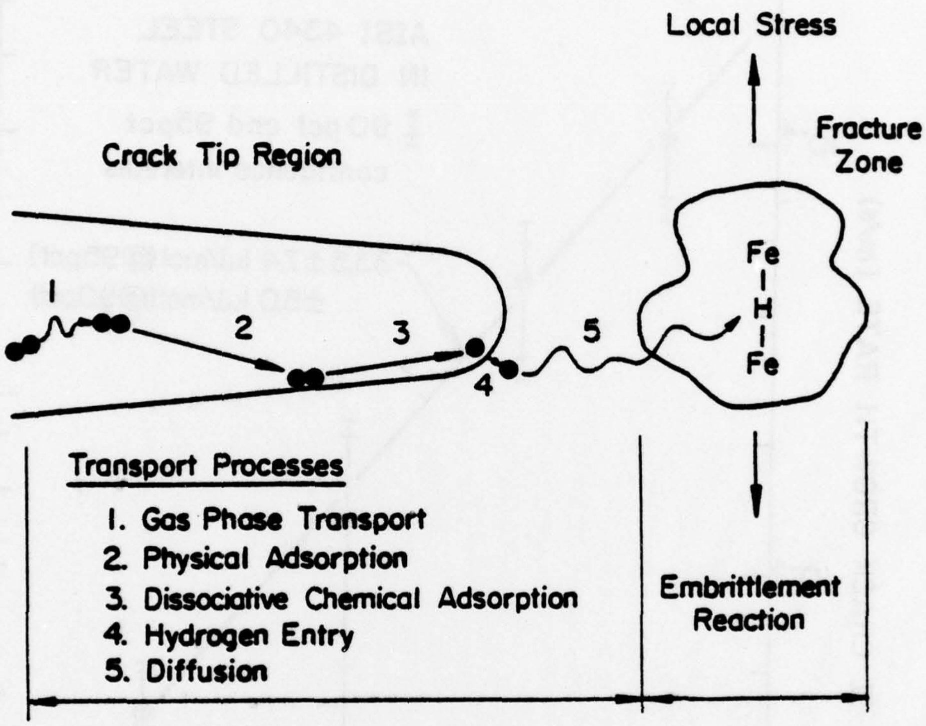
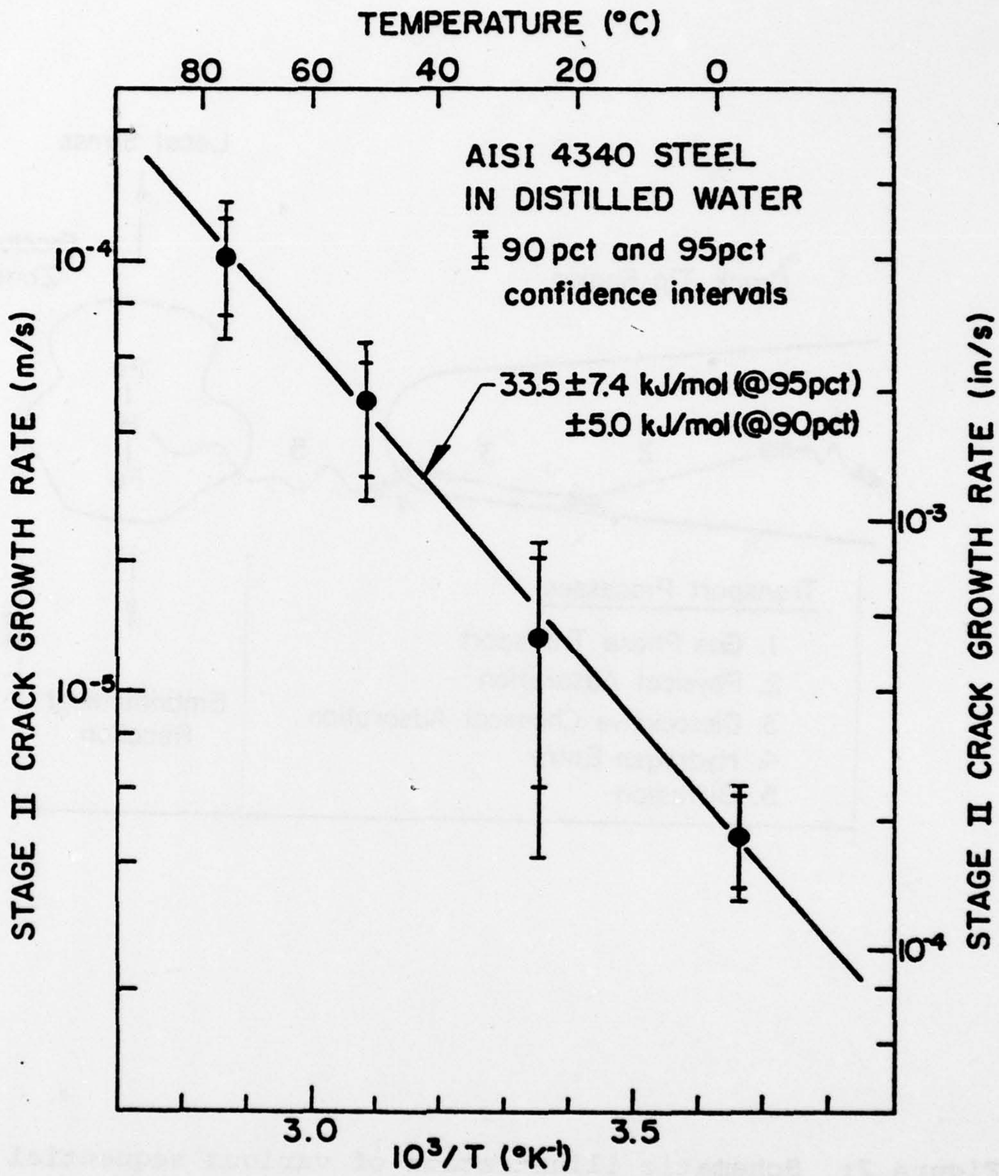


Figure 2: Schematic illustration of various sequential processes involved in embrittlement by external gaseous environments. (Embrittlement reaction is depicted schematically by the Fe-H-Fe bond).



(a)

Figure 3: Correlation between (a) the kinetics of Stage II (rate limited) crack growth under sustained load and (b) the rate of water vapor/metal (carbide) surface reaction for an AISI 4340 steel [32].

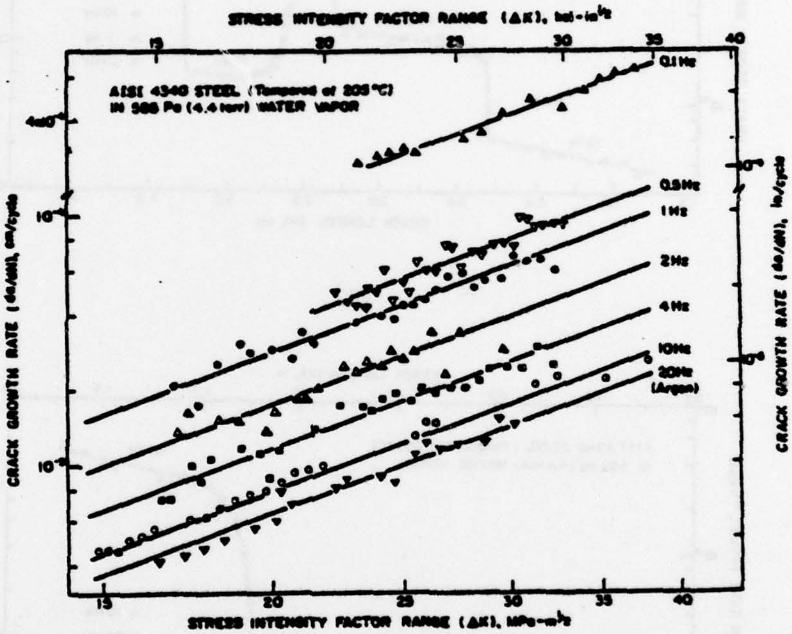
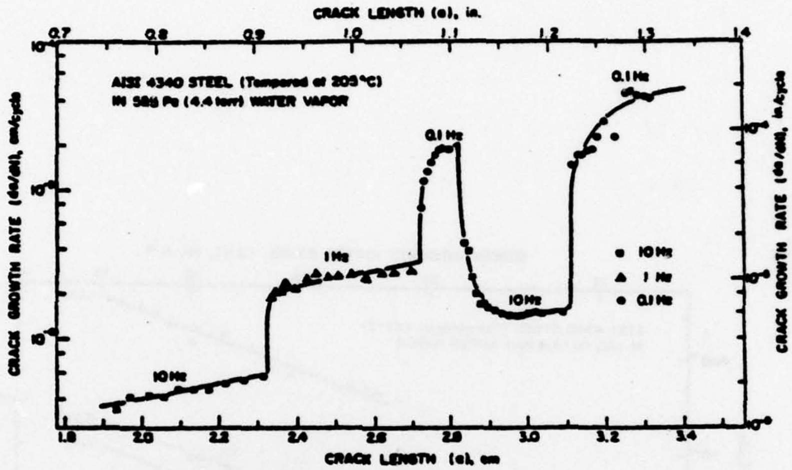
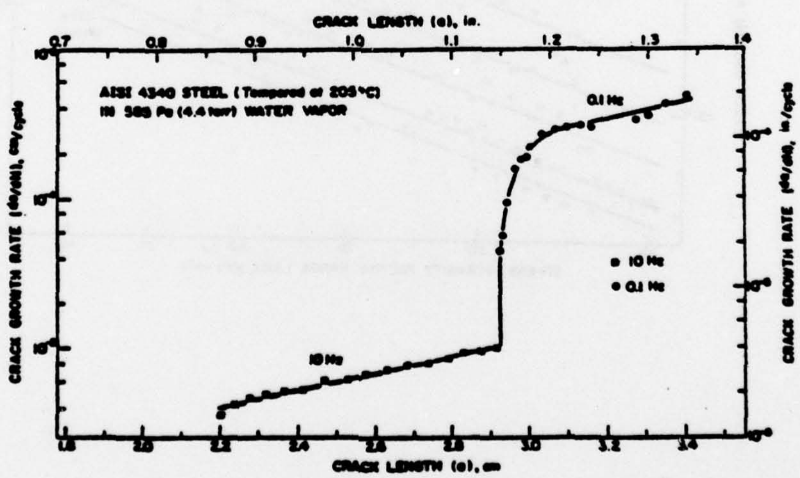


Figure 4: Room temperature fatigue crack growth kinetics on AISI 4340 steel tested in dehumidified argon and in water vapor (below K_{Iscc}) at R = 0.1 [31].



(a)



(b)

Figure 5: Room temperature fatigue crack growth response resulting from changes in cyclic load frequency [31].

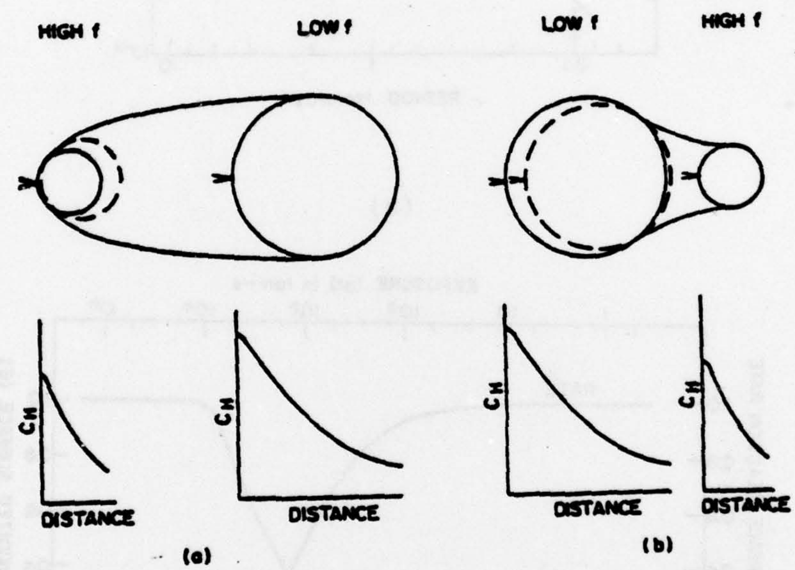
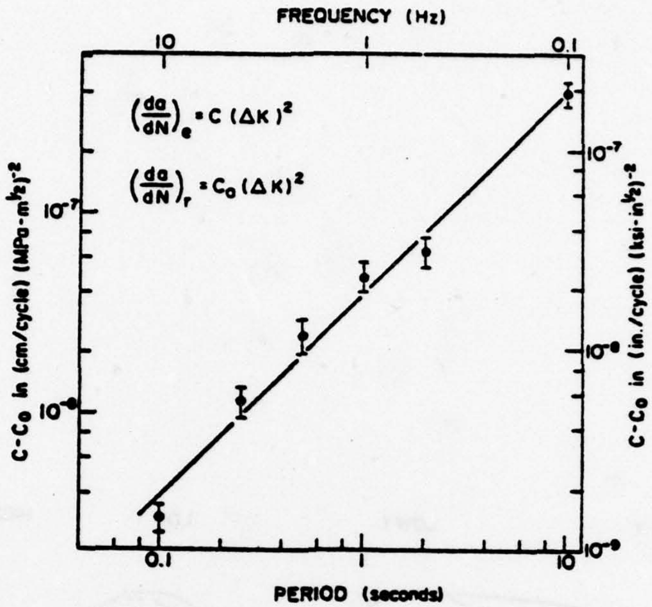
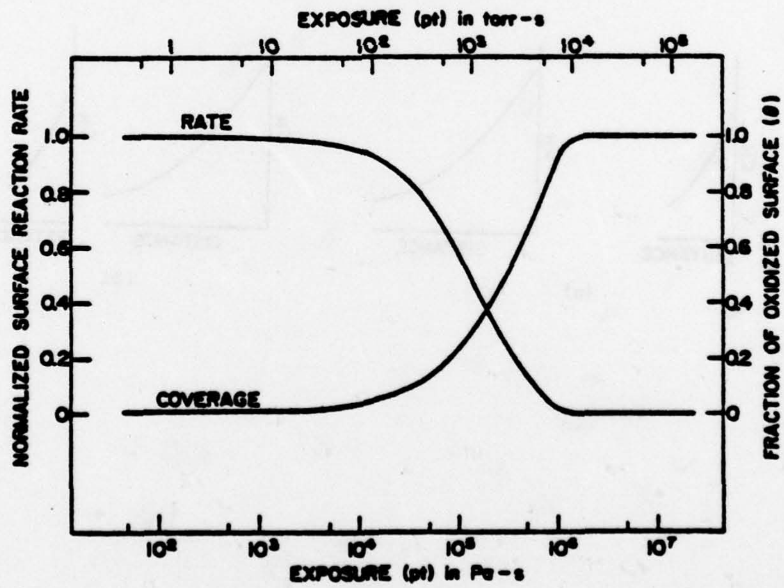


Figure 6: Schematic illustration of conceptual model for environment enhanced fatigue crack growth below K_{Iscc} [31].



(a)



(b)

Figure 7: Comparison between (a) the environment dependent component of fatigue crack growth as a function of cyclic load period and (b) the extent and normalized rate of reaction with water vapor as a function of exposure for an AISI 4340 steel at room temperature [31,32].

BASIC DISTRIBUTION LIST

Technical and Summary Reports April 1978

Organization	Copies
Defense Documentation Center Cameron Station Alexandria, VA 22314	12
Office of Naval Research Department of the Navy 800 N. Quincy Street Arlington, VA 22217	
ATTN: Code 471	1
Code 102	1
Code 470	1
Commanding Officer Office of Naval Research Branch Office Building 114, Section D 666 Summer Street Boston, MA 02210	1
Commanding Officer Office of Naval Research Branch Office 536 South Clark Street Chicago, IL 60605	1
Office of Naval Research San Francisco Area Office 760 Market Street, Room 447 San Francisco, CA 94102	1
Naval Research Laboratory Washington, DC 20375	
ATTN: Codes 6000	1
6100	1
6300	1
6400	1
2627	1
Naval Air Development Center Code 302 Warminster, PA 18964 ATTN: Mr. F. S. Williams	1
Naval Air Propulsion Test Center Trenton, NJ 08628 ATTN: Library	1
Naval Construction Batallion Civil Engineering Laboratory Port Hueneme, CA 93043 ATTN: Materials Division	1
Naval Electronics Laboratory San Diego, CA 92152 ATTN: Electron Materials Sciences Division	1
Naval Missile Center Materials Consultant Code 3312-1 Point Mugu, CA 92041	1
Commanding Officer Naval Surface Weapons Center White Oak Laboratory Silver Spring, MD 20910 ATTN: Library	1
David W. Taylor Naval Ship Research and Development Center Materials Department Annapolis, MD 21402	1
Naval Undersea Center San Diego, CA 92132 ATTN: Library	1
Naval Underwater System Center Newport, RI 02840 ATTN: Library	1
Naval Weapons Center China Lake, CA 93555 ATTN: Library	1
Naval Postgraduate School Monterey, CA 93940 ATTN: Mechanical Engineering Department	1

BASIC DISTRIBUTION LIST (cont'd)

Organization	Copies
Naval Air Systems Command Washington, DC 20360 ATTN: Codes 52031 52032	1
Naval Sea System Command Washington, DC 20362 ATTN: Code 035	1
Naval Facilities Engineering Command Alexandria, VA 22331 ATTN: Code 03	1
Scientific Advisor Commandant of the Marine Corps Washington, DC 20380 ATTN: Code AX	1
Naval Ship Engineering Center Department of the Navy Washington, DC 20360 ATTN: Code 6101	1
Army Research Office P.O. Box 12211 Triangle Park, NC 27709 ATTN: Metallurgy & Ceramics Program	1
Army Materials and Mechanics Research Center Watertown, MA 02172 ATTN: Research Programs Office	1
Air Force Office of Scientific Research Bldg. 410 Bolling Air Force Base Washington, DC 20332 ATTN: Chemical Science Directorate	1
Electronics & Solid State Sciences Directorate	1
Air Force Materials Laboratory Wright-Patterson AFB Dayton, OH 45433	1
Library Building 50, Rm 134 Lawrence Radiation Laboratory Berkeley, CA	1

Organization	Copies
NASA Headquarters Washington, DC 20546 ATTN: Code RRM	1
NASA Lewis Research Center 21000 Brookpark Road Cleveland, OH 44135 ATTN: Library	1
National Bureau of Standards Washington, DC 20234 ATTN: Metallurgy Division	1
Inorganic Materials Div.	1
Director Applied Physics Laboratory University of Washington 1013 Northeast Forthieth Street Seattle, WA 98105	1
Defense Metals and Ceramics Information Center Battelle Memorial Institute 505 King Avenue Columbus, OH 43201	1
Metals and Ceramics Division Oak Ridge National Laboratory P.O. Box X Oak Ridge, TN 37380	1
Los Alamos Scientific Laboratory P.O. Box 1663 Los Alamos, NM 87544 ATTN: Report Librarian	1
Argonne National Laboratory Metallurgy Division P.O. Box 229 Lemont, IL 60439	1
Brookhaven National Laboratory Technical Information Division Upton, Long Island New York 11973 ATTN: Research Library	1
Office of Naval Research Branch Office 1030 East Green Street Pasadena, CA 91106	1

C
April 1978

SUPPLEMENTARY DISTRIBUTION LIST

Technical and Summary Reports

Dr. T. R. Beck
Electrochemical Technology Corporation
10035 31st Avenue, NE
Seattle, Washington 98125

Professor I. M. Bernstein
Carnegie-Mellon University
Schenley Park
Pittsburgh, Pennsylvania 15213

Professor H. K. Birnbaum
University of Illinois
Department of Metallurgy
Urbana, Illinois 61801

Dr. Otto Buck
Rockwell International
1049 Camino Dos Rios
P.O. Box 1085
Thousand Oaks, California 91360

Dr. David L. Davidson
Southwest Research Institute
8500 Culebra Road
P.O. Drawer 28510
San Antonio, Texas 78284

Dr. D. J. Duquette
Department of Metallurgical Engineering
Rensselaer Polytechnic Institute
Troy, New York 12181

Professor R. T. Foley
The American University
Department of Chemistry
Washington, D.C. 20016

Mr. G. A. Gehring
Ocean City Research Corporation
Tennessee Avenue & Beach Thorofare
Ocean City, New Jersey 08226

Dr. J. A. S. Green
Martin Marietta Corporation
1450 South Rolling Road
Baltimore, Maryland 21227

Professor R. H. Heidersbach
University of Rhode Island
Department of Ocean Engineering
Kingston, Rhode Island 02881

Professor H. Herman
State University of New York
Material Sciences Division
Stony Brook, New York 11794

Professor J. P. Hirth
Ohio State University
Metallurgical Engineering
Columbus, Ohio 43210

Dr. D. W. Hoeppner
University of Missouri
College of Engineering
Columbia, Missouri 65201

Dr. E. W. Johnson
Westinghouse Electric Corporation
Research and Development Center
1310 Beulah Road
Pittsburgh, Pennsylvania 15235

Professor R. M. Latanision
Massachusetts Institute of Technology
77 Massachusetts Avenue
Room E19-702
Cambridge, Massachusetts 02139

Dr. F. Mansfeld
Rockwell International Science Center
1049 Camino Dos Rios
P.O. Box 1085
Thousand Oaks, California 91360

Professor A. E. Miller
University of Notre Dame
College of Engineering
Notre Dame, Indiana 46556

Dr. Jeff Perkins
Naval Postgraduate School
Monterey, California 93940

C
April 1978

SUPPLEMENTARY DISTRIBUTION LIST
(Continued)

Professor H. W. Pickering
Pennsylvania State University
Department of Material Sciences
University Park, Pennsylvania 16802

Professor R. W. Staehle
Ohio State University
Department of Metallurgical Engineering
Columbus, Ohio 43210

Dr. E. A. Starke, Jr.
Georgia Institute of Technology
School of Chemical Engineering
Atlanta, Georgia 30332

Dr. Barry C. Syrett
Stanford Research Institute
333 Ravenswood Avenue
Menlo Park, California 94025

Dr. R. P. Wei
Lehigh University
Institute for Fracture and
Solid Mechanics
Bethlehem, Pennsylvania 18015

Professor H. G. F. Wilsdorf
University of Virginia
Department of Materials Science
Charlottesville, Virginia 22903